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Our research on "Photonic Imaging Networks" is a part of the Graphics Server Consortium, which represents UCSD's continued participation in the DOD's Focused Research Initiative (FRI) program, supported by the BMDO via AFOSR.

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October 14, 1999

Dr. Kent Miller
AFOSR/NE
801 North Randolph Street, Room 732
Arlington, VA 22203-1977

Dear Dr. Miller:

Please find enclosed the final technical report for the Defense University Research Instrumentation Program grant: F49620-97-1-0399 entitled "Advanced Processing for High-Performance Optical and Electronic Systems." Should you have any questions about this report, please do not hesitate to contact me.

Sincerely,

Shaya

Y. Fainman
Professor

Final Technical Report

for

Defense University Research Instrumentation Program: Advanced Processing for High-Performance Optical and Electronic Systems

Sponsored by

Ballistic Missile Defense Organization

and

Air Force Office of Scientific Research

Under Grant F49620-97-1-0399

Grantee

The Regents of the University of California, San Diego

University of California , San Diego

La Jolla, CA 92093

Principal Investigators: Y. Fainman, S. Esener, E.T. Yu

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Program Manager: Dr. Kent Miller

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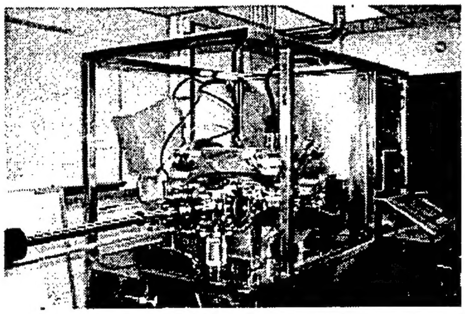
Acquired Equipment

1. Micro-Fabrication Facility – consisting of a micron and sub-micron feature mask generation station (e-beam lithographic system) and a CAIBE system capable of sub-micron resolution anisotropic (i.e. high aspect-ratio) etching.

   a) Chemically Assisted Ion Beam Etching System — $373,000

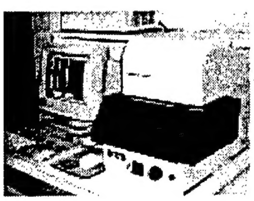


Funding contributed by:	
DURIP	$341,800
BMDO	$6,400
AFOSR	$11,000
NSF	$6,900
UC Matching Funds	$6,400

   b) E-Beam Lithography System — $105,600

Funding contributed by:	
DURIP	$17,300
BMDO	$36,000
UC Matching Funds	$62,400

2. Dektak 3 Auto Surface Profiler – sub-micron resolution 3D profilometer — $49,900



DURIP	$49,900

3. WaferSpec – lot of 4" Si wafer etching and preparation equipment consisting Of Tegal Si etcher, Vertaq spin rinse dryer, Pure Aire wet benches, Dexon 4 ft. laminar flow hoods and AG Assoc. RTP heat pulse — $87,800

Funding contributed by:	
DURIP	$10,000
AFOSR	$5,400
Rome Lab	$5,400
Army	$45,000
UC Matching Funds	$22,000

The total cost of the acquired micron and sub-micron fabrication and wafer preparation equipment was $616,300 consisting of $419,000 provided by DURIP and $90,800 from UC matched funds; an additional $42,400 and $16,400 from alternate BMDO and AFOSR funds, respectively; and $6,900 and $5,400 from the NSF and Rome Labs.

Projects Summary using Acquired Equipment

The acquired equipment is used to support the micro-fabrication and characterization needs of three projects at UCSD: "Photonic Imaging Networks" (Y. Fainman and A. Kellner), supported by the DOD's Focused Research Initiative (FRI) Program of BMDO via AFOSR; "GaN Microwave Power Amplifier" (P. M. Asbeck, S. S. Lau, and E. T. Yu), supported by BMDO via the U.S. Army Space & Strategic Defense Command; and "Interfacing Massively Parallel Computers to Terabit Fiber Links" (S. Esener, C. Fan) supported by BMDO via AFOSR.

Photonic Imaging Networks

(Y. Fainman, F. Xu, P. C. Sun, J. Thomas, R. Tyan, P. Shames, W. Nakagawa, P. Lin, D. Marom, D. Panasenko, K. Oba, Y. Mazerenko)

Our research on "Photonic Imaging Networks" is a part of the Graphics Server Consortium, which represents UCSD's continued participation in the DOD's Focused Research Initiative (FRI) program, supported by the BMDO via AFOSR. We have been investigating next generation photonic imaging networks for ultrahigh speed transmission of high-resolution images and image-format data. Our goals have been to develop transparent switching fabrics that can be easily integrated with existing and evolving network systems. Related research on high efficiency diffractive optics and computer generated diffractive optical arrays with multifunctionality and programmability, high speed polarization modulator arrays, and packaging of optoelectronic components and systems is funded by AFOSR, Rome Laboratory, DARPA, and NSF.

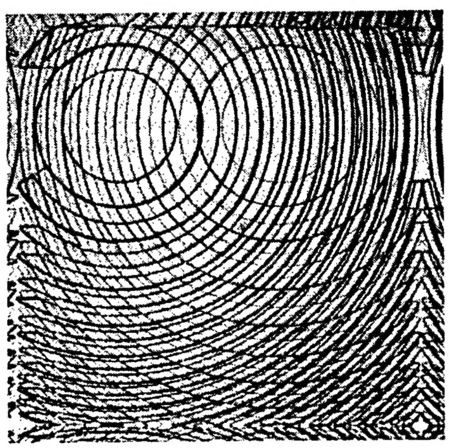


Fig. 1. CCD image of BCGH off-axis Fresnel lens. Note: two lenses are encoded into the same space, each responding to only one orthogonal polarization (i.e. act as optical flat for other polarization state).

We have advanced our investigations into diffractive optics with multifunctionality in polarization and color [1-3] as well as programmable diffractive optics employing natural birefringent and electrooptic nonlinear materials [4-7]. For example, we have fabricated spatially multiplexed array of polarization selective Fresnel lenses that was used in implementing optical multistage interconnection networks (see Fig. 1). We have also continued development of our research into artificial dielectric materials (nanostructures) for photonic device applications [1, 8-10]. The acquired DURIP equipment contributed to our fabrication efforts in the area of micro- and nano-scale features for artificial dielectrics and diffractive optics. Modern microfabrication techniques (dry etching, electron beam lithography, patterned regrowth, epitaxial growth, laser assisted growth, laser ablation, etc.) allow for fabrication of sub-micron structures which modify dielectric and semiconductor material properties such as birefringence, optical nonlinearity or opto-electronic interactions. For example, form birefringence or artificial

birefringence effects occur due to periodic microstructure boundaries between two isotropic dielectric materials with different dielectric constants. Form birefringent microstructures posses several unique properties that make them superior compared to these of naturally birefringent materials: (i) high strength of form birefringence, $\Delta n/n$, can be obtained by selecting substrate dielectric materials with large refractive index difference (here Δn and n are the difference and the average effective indices of refraction for the two orthogonal polarizations, respectively), (ii) the magnitude of form birefringence, Δn, can be adjusted by varying the duty ratio as well as the shape of the microstructures, (iii) form birefringence can be constructed using an isotropic as well as anisotropic substrate, allowing for fine tuning of the anisotropic properties of naturally birefringent materials, and (iv) form birefringent microstructures can be used to modify the reflection properties of dielectric boundaries. Artificial dielectric anisotropy due to form birefringence has been used to construct polarization optics components as well as polarization selective computer generated holograms. Form birefringent computer generated holograms were characterized experimentally using DURIP funded equipment.

Multifunctional diffractive optical elements have been designed for use in optoelectronic packaging as well as optical interconnect applications [2]. For example jointly with our collegaues from Bell Labs, Lucent Technologies we have developed a compact package to realize optical interconnections implementing a high speed I/O to optoelectronic VLSI chips. The basis of the package is a polarization selective di=ffractive optical element integrated with a CMOS/SEED array in a standard PGA carrier as shown in Fig. 2.

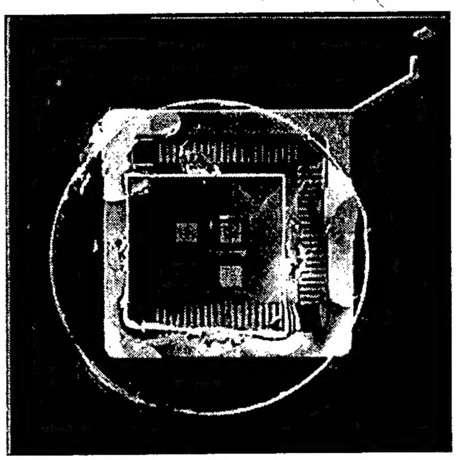


Fig. 2 Packaged OE-VLSI module.

We have also developed a novel switching fabric using a transparent optical multistage interconnect network (TOMIN), based on polarization-selective birefringent computer generated holograms technology being developed at UCSD [11, 12]. We have designed, fabricated and tested a 'folded' optical MIN system that permits switching high-speed signals between multiple input and output nodes using a simple and compact arrangement of diffractive optical and polarization rotation elements. In this system, optical routing is performed using bypass-exchange switches built of polarization sensitive birefringent computer generated holograms (BCGH) combined with electrically addressed polarization rotation devices. This transparent and scalable system can switch multiple high bandwidth communication lines or permit memory access and multiprocessor interconnections. For example, we built a folded optical MIN thjat allowed us to perform an 8X8 switching, allowing high SNR performance (see Fig. 3). The reconfiguration of the network is currently limited by the speed of the electrooptic modulators. To increase reconfiguration, we are developing a PLZT based polarization rotator array having much faster response times. Advances in fiber amplifiers and polarization compensation in a

single mode fiber may enable utilization of polarization dependent all-optical switches using optical fiber input and outputs.

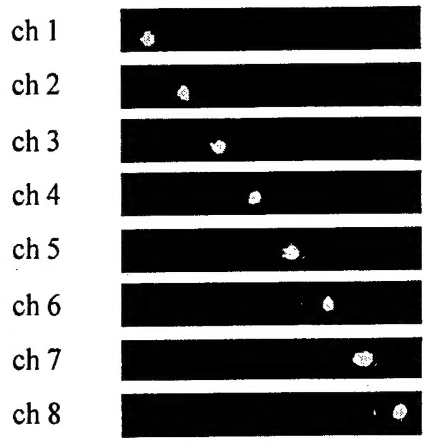


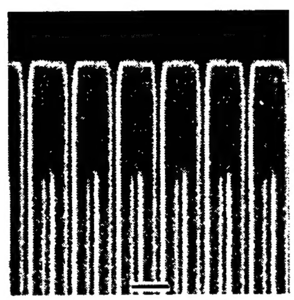
Fig. 3. CCD image of output of 8x8 MIN (3 layers of DBS) shows high contrast switching between eight output channels.

We have also continued our investigations into ultrahigh bandwidth parallel to serial and serial to parallel optical network interfaces [13, 14] for transmission over a fiber optic network as well as TOMINs. This data conversion method substantially increases the network throughput [15-17]. This multiplexer/demultiplexer approach is based on combining optical information processing that uses temporal spectrum domain wave mixing in a nonlinear optical material with that of conventional spatial Fourier transform wave mixing. Our Three-Wave Decoder [13, 14], operating with femtosecond response, implements time-to-space conversion for realization of multidimensional optical channels using ultrashort pulse three-wave mixing. These devices utilize three-wave mixing of spectral decomposition waves in nonlinear $\chi^{(2)}$ crystals of LBO. The DURIP funded equipment plays an integral part in the micro-fabrication of pulse shaping phase modulators and high-efficiency gratings. A nonlinear optical processor that is capable of true real-time conversion of spatial-domain images to ultrafast time-domain optical waveforms has also been developed [18]. The method is based on four-wave mixing between the optical waves of spectrally decomposed ultrashort pulses and spatially Fourier-transformed quasi-monochromatic images. To achieve efficient wave mixing at a femtosecond rate we utilize a cascaded second-order nonlinearity arrangement in a β-barium borate crystal with type II phase matching. We use this ultrafast technique to experimentally generate several complex-amplitude temporal waveforms, with efficiency as high as 10%, by virtue of the cascaded nonlinearity arrangement [18].

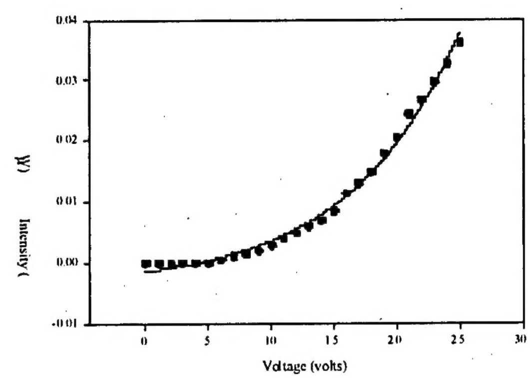
This equipment has also been used in the micro-fabrication of diffractive optical elements for use in ultrashort-pulse holographic memory systems [19-21]. We have demonstrated nonvolatile storage of femtosecond pulses in a photorefractive $LiNbO_3$ crystal with recording and readout of spectral holograms at a wavelength of 460 nm and 920 nm, respectively [22]. We have also designed and experimentally demonstrated a new pulse correlation technique that is capable of real-time conversion of a femtosecond pulse sequence into its spatial image [23]. Our technique uses a grating at the entrance of the system, thus introducing a transverse time delay (TTD) into the transform-limited reference pulse. The shaped signal pulses and the TTD reference pulse are mixed in a nonlinear optical crystal (LiB_3O_5), thus producing a second-harmonic field that carries the spatial image of the temporal shaped signal pulse. We show that the time scaling of the system is set by the magnification of the anamorphic imaging system as well as by the grating frequency and that the time window of the system is set by the size of the grating aperture. Our experimental results show a time window of ~20 ps. We also show that the chirp information of the shaped pulse can be recovered by measurement of the spectrum of the resulting second-

harmonic field. The DURIP funded equipment has been used for the micro-fabrication of the pulse shaping gratings and diffractive optics related to these projects.

The acquisition of the new micro-fabrication equipment has also enabled two new investigations: advanced micro-packaging for holographic memories and programmable meso-optic resonant near-field nano-structures. For example, motivated by increasing the speed and decreasing the driver power requirements, we have designed and fabricated first nanostructured electro-optic modulator shown in Fig. 4a. The preliminary charcterization results of the device are shown in Fig. 4b. The subwavelength featured mask was fabricated using the new SEM e-beam writer and the etching was done using our new CAIBE system. The Advanced Packaging project, funded by MURI, is focused on the design and development of optical memory systems consisting of 3-D holographic elements, VCSEL arrays and FPGA chips. Through development of our advanced rigorous coupled wave analysis (RCWA) modeling tools we have designed new micro- and nano-structured diffractive and holographic optical elements for beam shaping and beam steering, allowing for the interconnection of VCSEL array sources, angular multiplexed holographic elements and FPGA processing elements. We have also designed nanostructured AR coatings for high efficiency interconnects. The fabrication of such micro- and nano-structured elements is now possible with the acquisition of the new DURIP funded micro-fabrication system.



(a)



(b)

Fig. 4. (a) SEM micrograph of the fabricated inter-digital electrodes pattern. The scale bar in the photograph is 1 μm. (b) Light intensity through a pair of cross polarizers as a function of driving voltage on the modulator. The subwavelength featured mask was fabricated using the new SEM e-beam writer and the etching was done using our new CAIBE system.

The current trend in developing high performance computing and communication systems is towards increasing parallelism in addition to speed, establishing a growing need to reduce the scale, thus increasing the functionality of a given volume of a system. Electrically and/or optically programmable meso-scale photonic devices can introduce multiple functionality into the same volume. Another approach to volume utilization takes advantage of optical near-field interactions in resonant nanostructures, much smaller than the wavelength. Under an AFOSR funded research project, we have focused our investigations on developing resonant artificial dielectric EO and nonlinear (NL) optical nanostructures that utilize near-field optical properties enabling multifunctionality and electrical programmability on smaller than the optical wavelength scale. We are also studying the near field interactions between meso-scale devices in high density applications as well as optical I/O to guided waves and to the free space modes utilizing near-field phenomena. The fabrication of these meso-optic and resonant nanostructures has been enabled by the installation of the new DURIP equipment.

The new micro-fabrication system has also allowed for advances in our fabrication of nano-structured optical elements on porous-silicon based devices for advanced detection of chemical and biological agents. The applied physics portion of this DARPA funded project, "Development of a Sensor for Nerve Warfare Agents Based on a Porous Si Interferometer," is focused on the development of micro optical elements integrated with porous silicon elements. Porous silicon, with its low density, allows for exceedingly high surface area to volume ratios. The development of chemical and biological detectors based on porous silicon substrates capitalizes on the surface area to generate a highly sensitive optical interferometer. By coating the surface with varying catalytic agents a highly selective and sensitive detector can be fabricated. Using our RCWA modeling tools we have designed nano-structured optical filters to enhance this sensitivity and make a highly efficient, compact and rugged detector design.

<u>GaN Microwave Power Amplifier</u>
(P. M. Asbeck, S. S. Lau, and E. T. Yu, PI's)

The GaN Microwave Power Amplifier (GaNMPA) program, supported by BMDO via the US Army Space & Missile Defense Command, is a focused, multi-institution research and development effort directed towards the development of high-power, microwave-frequency field-effect transistors (FET's) and of X-band power amplifiers based on III-V nitride materials and device technology. Research at UCSD conducted under this program is directed primarily towards the development of materials and processing technology for low-leakage Schottky contacts and low-resistance Ohmic contacts to n-type nitride semiconductors, and the investigation of heterostructure materials and device physics for improvement of contact properties and overall device performance. Our investigations have emphasized materials and processing for high-quality contacts that are robust and manufacturable [24-28], and the characterization and understanding of nitride heterostructure materials and device physics for optimization of epitaxial layer design and fabrication processes. In the course of this work, a significant new understanding of polarization effects in III-V nitrides, and their influence on device characteristics, has emerged [29-32]. UCSD has been one of the leaders in research on this topic.

In the area of metal-nitride contacts, we have performed extensive characterization of Schottky contact properties of a variety of metals to n-type GaN, thereby deriving an understanding of the relationship between metal work function and Schottky barrier height. This understanding has subsequently served to guide our efforts to develop low-leakage Schottky gate contacts and low-resistance Ohmic source and drain contacts essential for HFET devices intended for use in microwave power amplifier applications. Based on these fundamental studies we have developed a novel approach, illustrated in Figure 5, for fabrication of Ohmic contacts to n-type AlGaN/GaN transistor structures with extremely low contact resistance. The conventional approach for Ohmic contact formation entails the deposition of Ti/Al multilayer metallization and subsequent annealing to induce a reaction between the Ti metal and the nitride

semiconductor to form a TiN alloy and a highly n-type near-surface semiconductor region. In the novel "advancing" metallization scheme developed at UCSD, additional Ti is incorporated and a reaction is induced to form a larger n-type near-surface region via reaction of the nitride semiconductor with the Ti layer. This approach yields an order of magnitude improvement in contact resistance compared to the conventional metallization scheme. An additional reduction in contact resistance can be obtained by implantation of Si dopants in the contact regions, also illustrated in Figure 5. This approach has been demonstrated to yield, by itself, a reduction in contact resistance by roughly an order of magnitude. In combination, ion implantation and the advancing metallization process can yield an improvement in contact resistance of roughly two orders of magnitude. This reduction in contact resistance has a very substantial impact on efficiency and power output of nitride HFET's at microwave frequencies.

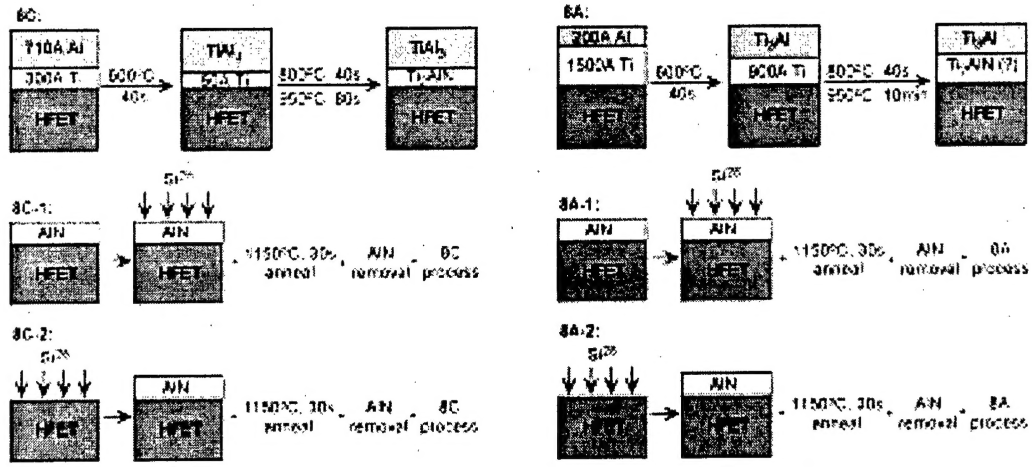


Fig. 5. (Left) Conventional Ti/Al Ohmic contact fabrication process combined with Si ion implantation, which reduces contact resistance by roughly an order of magnitude. (Right) "Advancing" Ohmic contact fabrication process combined with Si ion implantation. The "advancing" contact metallization combined with ion implantation reduces contact resistance by roughly two orders of magnitude.

Research at UCSD under this program has also led to extremely important breakthroughs in the understanding of nitride semiconductor heterostructure device physics, specifically with regard to spontaneous and piezoelectric polarization effects. Device analysis performed at UCSD first brought to light the importance of piezoelectric effects in the behavior of AlGaN/GaN HFET's, specifically in the realization of extremely high channel carrier densities even in the absence of intentional doping. It rapidly emerged that these effects, and related spontaneous polarization effects, have a profound impact on electric field, potential and mobile carrier distributions in nearly all nitride heterostructure devices. In addition, polarization effects provide a new approach for the engineering of nitride heterostructure devices with improved performance. Early work at UCSD on this subject demonstrated that polarization effects could be exploited to engineer Schottky barrier structures for the gate region of an AlGaN/GaN HFET with a Schottky barrier height increased by ~0.4V compared to that in a conventional structure, and with a corresponding reduction in gate leakage current by a factor of approximately 1000. Currently we are working actively on the design and fabrication of a variety of nitride semiconductor device structures in which polarization effects are a key aspect of the device design. It is anticipated that the chemically assisted ion-beam etching system and the electron-beam lithography system will play key roles in the fabrication and demonstration of these devices.

Interfacing Massively Parallel Computers to Terabit Fiber Links
(S. Esener, C. Fan)

Supported by BMDO via AFOSR This research effort addresses device technology development for interfacing electronic parallel computers and/or local networks to terabit fiber links. Such devices are required in order to match the very large temporal bandwidth available in optical fibers to the aggregate I/O bandwidth achievable by parallel computers or local networks/clusters of workstations.

The specific objective of the program involving the DURIP provided equipment was to study the refractive index modulation in III-V semiconductor multiple-quantum-well (MQW) devices under high optical pulsed power. Traditionally, MQW devices have been limited to the use of amplitude modulation at low optical intensity. Although, the index modulation in MQW material is considerably higher than in other electro-optical materials, this effect is masked by the absorption leading to phase modulated devices with very high insertion loss.

During the course of this program, we have showed theoretically and experimentally that the refractive index modulation in MQW materials although small in magnitude also exists above absorption saturation. This finding indicates the potential use of MQW materials and devices for phase modulation with low insertion loss when biased properly. A phase-shift interferometry method has been developed to measure the index change with a resolution of $\lambda/2500$ in MQW devices subjected to high intensity illumination. With this method we have measured index changes in a MQW material under absorption saturation as 0.05%. We also believe that this modulation is limited by electric field screening due to the capture rates of the carriers of the materials we used.

The material used in these experiments was designed to operate at wavelengths compatible with commonly available high power lasers, such as YAG and YLF lasers, near 1.064μm. InGaAs/InAlGaAs quantum well material can be grown on GaAs wafers to show an exciton resonance at the desired wavelength. For operation at or near 1.06μm, however, the indium concentration in the InGaAs well material must be near 20%. This represents close to a 2% lattice mismatch with respect to the GaAs substrate. Strain relief occurs in the form of dislocations that propagate to the surface, degrading device performance. Buffer layers can mitigate strain effects caused by the lattice mismatch. Such layers are grown underneath the quantum well material to gradually change the lattice constant to that of the well material.

In order to fabricate devices that take advantage of phase modulation in MQW materials we are now using the DURIP provided equipment described above. The CAIBE machine allow us to fabricate MQW phase modulators as shown in Figure 6 and 7 and the Dektak profilometer was instrumental in controlling the mirror smoothness and the bevel angle used between the front and back surface of our devices for measuring the phase modulation as a shift of the interference pattern. Specifically, PIN diode modulators were fabricated in the epitaxial layers on the front surface of the GaAs wafer sample. The backside of the sample was mechanically polished with an intentional wedge to generate interference fringes at a particular spatial frequency. Then a high reflectivity (at near-IR wavelengths) gold mirror was thermally evaporated onto the backside of the sample. The result is a reflective mode surface normal MQW modulator with an internal cavity to generate interference fringes.

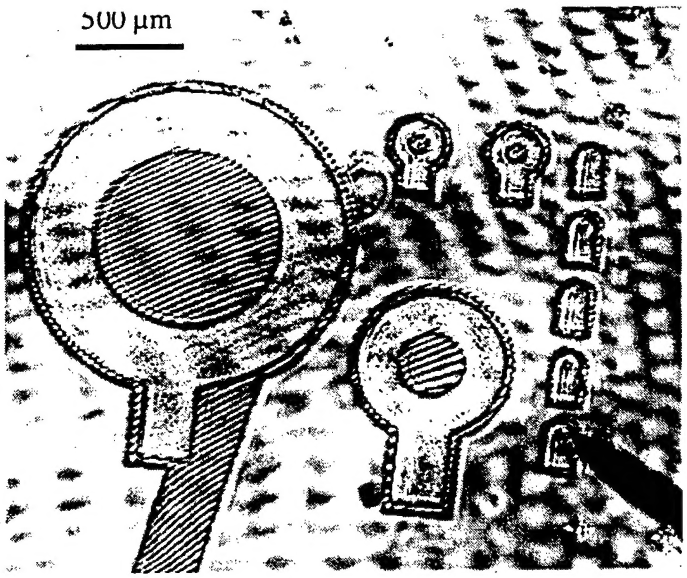


Fig. 6: Several sizes of ring diodes fabricated on the InGaAs/InAlGaAs MQW material. Coherent illumination readily shows the straight interference fringes generated in diode windows due to the sample wedge angle. An electrical probe tip is visible at the lower right. The straight bar leading into the large size modulator is a break in the ground plane metallization caused by shadowing of the sample holder clip during the metal evaporation. Interference fringes can be seen in this area as well as the diode windows. Applied electric field results in the shifting of the interference fringes.

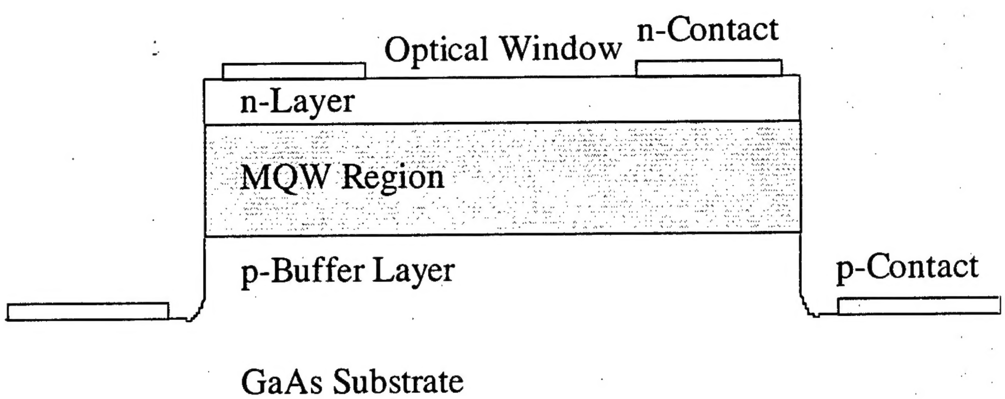


Fig. 7: Cross-section view of the PIN modulator

The MQW material was processed into PIN ring diodes, with an optical window in the center of a ring contact. See Figure 7 for a diagram of the diode structure. Deep mesa isolation was used to electrically separate the modulators. A common ground plane, the p-doped buffer layers, was used for one electrical contact. The other contact, the n-doped cap layer, was located on top of the mesa. Electrical contacts were made using annealed AuGe and CrAuZn metallization. Related research on OE device and component development for 3-D packaged systems was funded by DARPA, AFOSR and Hughes.

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